ACOUSTIC TOMOGRAPHY IN THE CANARY BASIN: MEDDIES AND TIDES

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Abstract: *An acoustic propagation experiment over 308-km range conducted in the Canary Basin in 1997–1998 was used to assess the ability of ocean acoustic tomography to measure the flux of Mediterranean water and Meddies. Instruments on a mooring adjacent to the acoustic path measured the southwestward passage of a strong Meddy in temperature, salinity, and current. Over 9-months of transmissions, the acoustic arrival pattern was an initial broad stochastic pulse varying in duration by 250 to 500 ms, followed eight stable, identified ray arrivals. Small-scale sound speed fluctuations from Mediterranean water parcels littered around the sound channel axis caused acoustic scattering. Internal waves contributed more modest acoustic scattering. Based on simulations, the main effect of a Meddy passing across the acoustic path is the formation of many early-arriving, near-axis rays, but these rays are thoroughly scattered by the small-scale Mediterranean water fluctuations. A Meddy decreases the deep-turning ray travel times by 10–30 ms. The dominant acoustic signature of a Meddy is therefore the expansion of the width of the initial stochastic pulse. While this signature appears inseparable from the other effects of Mediterranean water in this region, the acoustic time series indicates the steady passage of Mediterranean water across the acoustic path. Tidal variations caused by the mode-1 internal tides were measured by the acoustic travel times. The observed internal tides were predicted using a recent global model for such tides derived from satellite altimetry.*

Keywords: *acoustic tomography, salt lenses, acoustic scattering, Canary Basin, mode-1 internal tide*

1. INTRODUCTION

Meddies are compact, coherent eddies of warm, salty Mediterranean water, also known as salt lenses [1, 2, 3]. First discovered in the early 1980s, Meddies reside near the sound channel axis at 1000–1200 m depth in the Eastern North Atlantic. They likely contribute to the Mediterranean salt tongue, a water mass at mid-depths that extends into the subtropical Western North Atlantic. Meddies are nearly circular, with a horizontal scale of about 100 km and a vertical extent of several hundred meters. Currents within a rotating Meddy are about 20 cm/s, while Meddies move at about 4 cm/s. Meddies typically move from the Mediterranean outflow northward up the Portuguese coast, or southwestward through the Canary Basin. The warm and salty characteristics of Mediterranean water are, of course, density compensating, but these properties also mean that Meddies have a sound speeds that are 10–20 m/s faster than ambient sound speeds. In recent years, seismic techniques have been used to obtain detailed images of Meddies. In the Eastern North Atlantic, Mediterranean water masses also appear as submesoscale structures, cyclones, and filaments near the sound channel axis, and small-scale, stochastic water parcels littered around the sound channel axis. Meddies are often surrounded by the latter.

With their clear sound speed signatures, Meddies have been examined as candidates for observation by ocean acoustic tomography [4]. Since Meddies are density compensated, they are difficult to locate or quantify. Observation of Meddies by an integrating tomographic array was intriguing, while the oceanographic need for assessing the flux of Mediterranean water was compelling. While the sound speed of Meddies represent the obvious approach for measurement by travel-time tomography, the acoustic signatures of Meddy currents [5] or horizontal refraction [6] were examined in the 1990s. Others examined the relative vorticity of Meddies as a possible approach to observation. All such secondary signals are extraordinarily (and impractically) small. In 1997, Fabienne Gaillard and Thierry Terre at IFREMER, Brest, France designed the "Canary-Azores-Madeira Basin Integral Observing System" (CAMBIOS) experiment to test the ability of acoustic tomography to measure the flux of Meddies [7, 8]. CAMBIOS took place in the Canary Basin from July 1997 to April 1998 (Fig. 1). The analysis of these data was interrupted by other projects, but a new analysis has shed light on the acoustic signals of Meddies and Mediterranean water. The reader is referred to Dushaw, Gaillard, and Terre [7] for further details of the analysis summarized here. All of the acoustic, moored, hydrographic and ancillary data associated with CAMBIOS are openly available (see [7] and associated links).

2. CAMBIOS TOMOGRAPHY

The CAMBIOS acoustic array consisted of five moorings denoted T1-T5 deployed across the Canary Basin between the Canary and Azores islands (Fig. 1). Because of a number of instrument failures, acoustic data were mainly obtained between the T1 and T2 moorings. The T1 mooring was located at 31.9988°N, 19.8008°W in about 4150 m ocean depth, and the T2 mooring was located to the northwest at 34.2473°N, 21.75002°W in about 5275 m ocean depth. The acoustic propagation was over 308.692 km range over the smooth Madeira Abyssal Plain. The acoustic sources, at 660 m and 700 m depths, began reciprocal transmissions on yearday 190 in June 1997 that continued for 265 days (Fig. 3), ending on yearday 454 in early April 1998. The acoustic sources operated at a source level of 180 dB Re 1 µPa @ 1 m with 400 Hz center frequency and 100 Hz bandwidth. The signals were received by hydrophones mounted just above the source on the receiving mooring.

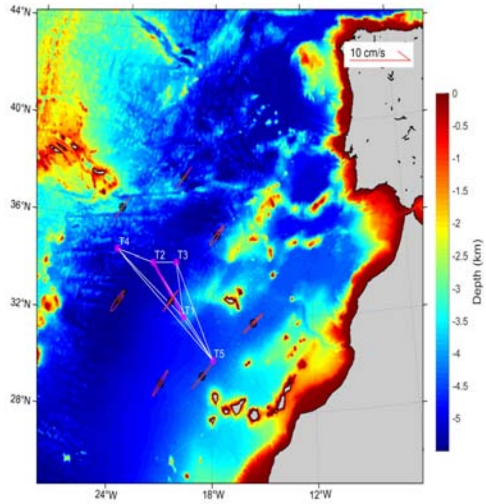

Fig. 1: The CAMBIOS array was located across the Canary Basin and oriented so as to observe the southwestward flux of Mediterranean water. The Canary Basin is the primary avenue for movement of Mediterranean water into the western Atlantic. The M_2 tidal current elipses are denoted in red. The T1-T2 acoustic path was along the small minor axis of tidal current, hence the observed signal from tidal currents was small. Azimuthal equal area projection.

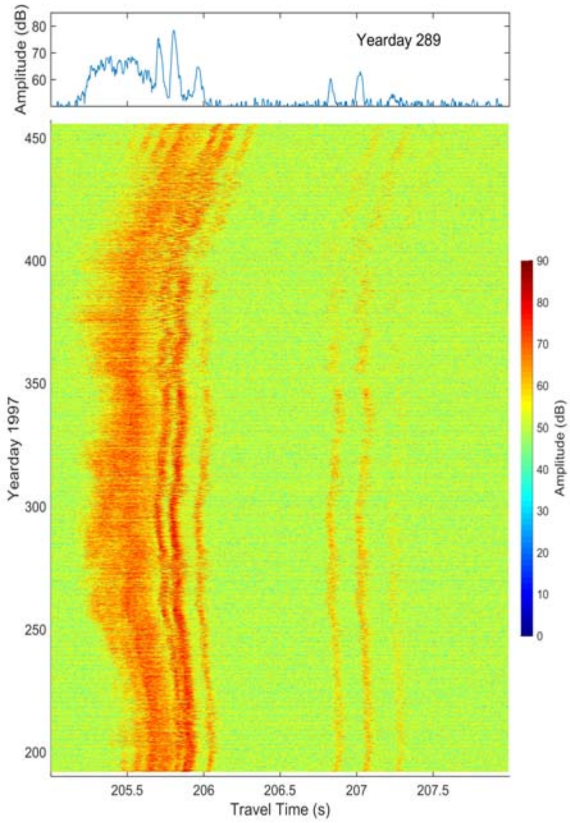

Fig. 2: Acoustic receptions obtained along the T1–T2 acoustic path. The profile of a reception on Yearday 289 is given in the top panel. About seven stable ray arrivals are evident, including a doublet arrival that appears in the top panel as the largest amplitude peak and the three late-arriving bottom reflected rays.

3. MEDDIES AND MEDITERRANEAN WATER

The acoustic receptions consist of an initial stochastic section varying by 250-500 ms width, followed by six distinct ray arrivals (Fig. 2). The ray arrivals are readily identified by ray predictions using either climatology, or available CTD data obtained during the experiment. The ray arrivals consist of two groups of three arrivals, and the middle arrival of each group actually consists of two coincident ray arrivals of opposite arrival angle. The hydrophone arrays were, alas, not capable of distinguishing even the sign of ray arrival angle. In this region of the Eastern North Atlantic, the time front is reversed from that in other regions of the ocean in that the near-axis acoustic signals arrive first, followed by the deep-turning arrivals. The late-arriving rays reflect once or twice from the sea floor near mooring T1. We call the initial arrival the "overture", in parallel with the term "finale" that has been used for the similar arrival at the end of the arrival pattern in other regions.

The last ray arrival is weak and it was not obtained by the ray predictions using smooth sound speed. In this region, small-scale sound speed fluctuations from Mediterranean water significantly affect the acoustic propagation. Internal-wave variations contribute somewhat [9], but the parcels of Mediterranean water that litter the sound channel axis provide the dominate effects. A stochastic model for the sound speed variations was developed, based on a similar model employed for modeling variability in Fram Strait [10]. The effects of small-scale variability on acoustic propagation are two-fold. First, the acoustic scattering extends the branches of the time front to later arrival times, and this extension accounts for the last ray arrival. The last ray arrival is, in fact, a "shadow-zone" arrival, sometimes called a "non-geometric" arrival (a misnomer, apparently) – a shadow-zone arrival of a bottom-reflecting ray recorded above the sound channel axis. Second, the near-axis propagation is considerably scattered, which accounts for the stochastic nature of the overture. The variable, yet persistent, overture is indicative of the persistent presence of Mediterranean water along the T1-T2 acoustic path.

The characteristic sound speed amplitudes and shapes of Meddies are fairly well defined, so it was a simple matter to simulate the expected travel time signals of a typical Meddy as it crosses the T1-T2 acoustic path. Indeed, all of the five CAMBIOS moorings were well instrumented with thermistors, current meters and ADCPs, and a Meddy was directly observed as it moved over the T3 mooring adjacent to the T1-T2 acoustic path. The observed direction of motion was to the southwest, in accordance with the general direction of motion for Meddies in the region [2]. The observed Meddy therefore likely crossed the T1-T2 acoustic path about yearday 280. Simulations show that the effects of a Meddy crossing the T1-T2 acoustic path are a decrease in the deep-turning ray travel times of 10-30 ms and the formation of several more early ray arrivals. A Meddy is fairly localized, so its effects on the travel times of deep-turning rays is relatively small. The travel time variations of the overture are more a consequence of the formation of new rays, rather than a decrease in travel time. When coupled with the ever-present stochastic scattering by Mediterranean water, the signals of Meddies are, unfortunately, not obvious to detect. There is an inherent ambiguity between the scattering by small parcels of

Mediterranean water and the creation of new rays by the passage of a Meddy. Both effects indicate Mediterranean water, however. The passage of a Meddy might be expected to be a singular event in the acoustic time series, but no such event or events were detected. Rather, the broad overture persisted for essentially the duration of the CAMBIOS experiment.

Ray tracing shows that a typical Meddy event has non-linear acoustical effects. A Meddy is a compact feature of perhaps 15 m/s localized increase in sound speed right at the sound channel axis. The appearance of a Meddy causes acoustic rays to split into two groups of rays that travel above and below the Meddy. Between effects such as this and the obvious effect of the scattering from small-scale features littered around the sound channel axis, the interpretation of the acoustic signals as a measure of Meddy motion and the flux of Mediterranean water has proved to be ambiguous.

4. MODE-1 INTERNAL TIDES

In recent years the remarkable predictability of mode-1 internal tides in open-ocean regions of the oceans has become apparent [11, 12]. Models for this variability have been derived from satellite altimetry with the ability to predict travel time variablity observed by acoustic tomography (Fig. 3). One new motivation for examining the CAMBIOS data was the expectation that internal tides may have been observed, and those signals may be predictable. Observations such as these in the Canary Basin would provide further evidence for the general predictability of these internal waves in the world's oceans.

The ray arrivals in the CAMBIOS data were tracked and filtered to obtain measurements of the tidal variations in travel time. The difference of reciprocal travel times were computed, but the data proved to be quite noisy. Further, the tidal signal from currents predicted from global barotropic tidal models was small. The acoustic path was, not by coincidence, aligned along the minor axis of the tidal currents (Fig. 1). Reasons for the excessive noise include the weak acoustic sources, the inability to separate upward and downward traveling rays, and the enhanced scattering of the acoustic signals. The sum of reciprocal travel times exhibited a stronger tidal signal, and these signals were indeed mostly predicted by the global internal tide model (Fig. 3). In this preliminary comparison, observed amplitudes were larger than predicted, while the observed and predicted phases were in agreement. A further refinement of the comparison, requiring a proper inversion of the travel times to estimate variations in temperature, may obtain better agreement. Note that to obtain the predicted travel time, one has to convert estimates of sea-surface height to internal displacement, to internal temperature, to sound speed, and finally to travel time. Similar results were obtained using either climatology or available CTD data for the hydrographic conditions.

5. DISCUSSION

The aim of CAMBIOS was to test the ability of acoustic tomography to measure properties of Mediterranean water and Meddies as they move southwest though the Canary Basin. The results of the observations were ambiguous, mainly because of the influence of ubiquitous small-scale Mediterranean water parcels, littered along the sound channel axis, on the acoustic propagation. While the signatures of a Meddy in the acoustic arrival pattern are clear, they are obscured by the acoustic scattering. The observations indicate a persistent presence of Mediterranean water, of whatever form, however.

While deep-turning ray travel times are amenable to estimating the temperature variations, some of which may be caused by Meddies, these signals are ambigous with other ocean variability. In particular the acoustic path was, by design, across the Azores front with a 3°C change in temperature. Movement of this front would affect travel times of deep turning rays in a way that is similar to the signals of a Meddy.

The data suffered from several problems. Issues that could be resolved by refined experiment design are an increase in source level and the use of hydrophone arrays to

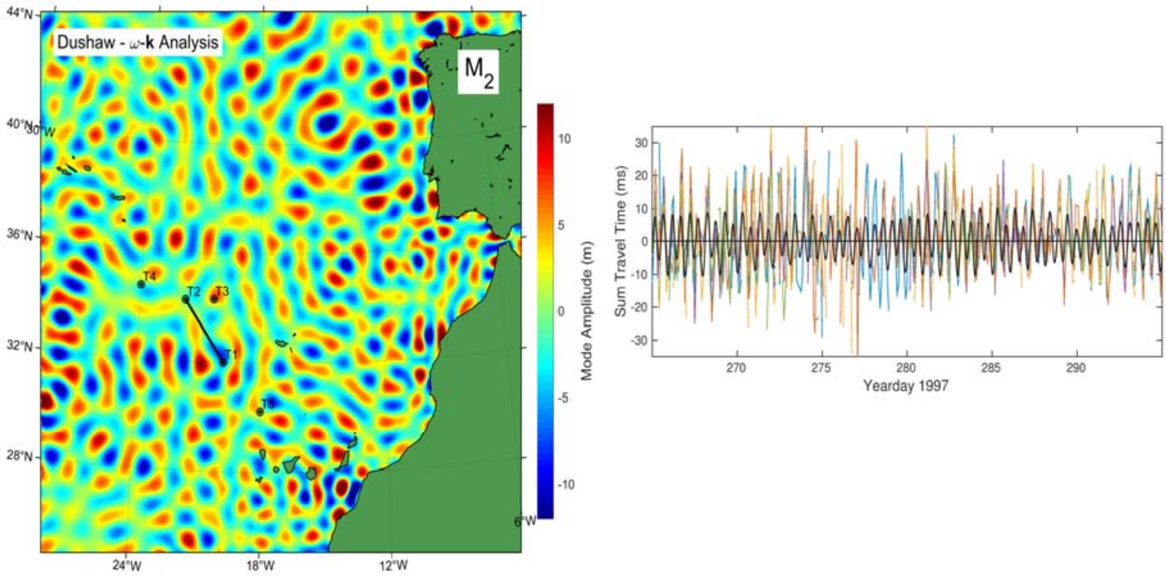

Fig. 3: (Left panel) A snapshot of mode-1, M_2 internal tides for the CAMBIOS region derived from the empirical model of Dushaw [11]. The internal tide field is a complicated interference pattern. The black segment indicates the T1-T2 acoustic path. (Right panel) Thirty days of high-frequency (>0.5 cpd) travel times, the sum of reciprocal travel times. The travel times exhibit the obvious signal of mode-1 internal tides which compares favorably to the independent prediction (black line).

resolve and distinguish the ray arrival angles. In addition, reciprocal transmissions were separated in time by about 20 minutes, thus offering an imperfect removal of the fluctuations of sound speed variations in the differential travel times. The enhanced acoustic scattering in the region caused by Mediterranean water was a complication presented by nature. The relatively small signal of Meddies in deep-turning ray travel times (10-30 ms) requires optimal measurements to resolve.

The barotropic tidal currents offered a signal that was too small to resolve, particularly given the enhanced noise of the observations. The baroclinic tidal variations, caused by the displacements of mode-1 internal tides, were significant, however, and mostly predicted by a recent global model for these tides. Such agreement between observations and prediction is consistent with similar comparisons obtained elsewhere in the world oceans.

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